Technical Note DOER-C9
November 1999

Phytoreclamation of Dredged Material: A Working Group Summary

PURPOSE: The purpose of this technical note is to summarize the discussions and conclusions of the Phytoreclamation Working Group meeting held at the U.S. Army Engineer Research and Development Center (ERDC), Waterways Experiment Station (WES), Vicksburg, MS, March 16-18, 1999. The meeting was held as part of the Dredging Operations Environmental Research Program, Vegetation Management Work Unit.

BACKGROUND: Dredged material, in simple terms, is nothing more than displaced topsoil that enters and eventually is removed from navigable waterways. Although contaminant discharges into waterways over time have resulted in contamination of bottom sediment, only a small percentage of dredged material is contaminated by definition. Once sediment is removed from a waterway by dredging, it must be placed outside the navigation channel. One alternative to open water discharge is confined upland placement. In many areas where dredging is frequent and space for confined disposal facilities (CDF) is at a premium, the cost for confined upland placement is rising or this alternative is not available. One solution is to utilize dredged material as a soil resource offsite, reducing the need for construction of additional CDFs. For contaminated dredged material that was, has been, or will be determined suitable for upland placement in a CDF, the next logical step is to make it suitable for reuse offsite as a soil material by reducing contaminant concentrations to within regulatory compliance concentrations.

The Vegetation Management Work Unit is part of the Contaminated Sediments Focus Area of the Dredging Operations and Environmental Research (DOER) Program. The focus of the work unit is to determine vegetation management alternatives that enhance cleanup and reuse and/or minimize adverse effects of contaminants in upland CDFs. One task in the work unit includes phytoreclamation, the use of plants to reduce contaminant concentrations in dredged material. Phytoreclamation of dredged material has not previously been considered as a cleanup alternative, and little information on application to dredged material is available. Previous efforts in other areas of dredged material research relied on focussed discussion of a problem and consensus by a working group of peers. The working group approach resulted in the successful completion of research on contaminant mobility in plants and animals at the Blackrock Harbor, Connecticut, CDF, under the Field Verification Program. Therefore, the same approach was enlisted to evaluate phytoreclamation.

PHYTORECLAMATION WORKING GROUP: A list of potential participants was assembled from personal knowledge and previous interactions at professional meetings relating to phytoreclamation. Selections of participants were made to ensure the working group would have a broad knowledge base and ability to interact constructively. The participants of the working group and their affiliation are provided in Table 1. The participants were invited by WES and were selected based on their professional experience and interest in phytoreclamation vested in sound, scientific judgment. The newly formed Phytoreclamation Working Group met at WES on March 18-20, 1999. The purpose of the meeting was to discuss the issues relating to phytoreclamation of contaminants

Table 1
Members of the Phytoreclamation Working Group

Name	Title	Affiliation
Mr. Richard A. Price	Research Agronomist	WES, Vicksburg, MS
Dr. Charles R. Lee	Soil Scientist	WES, Vicksburg, MS
Dr. John W. Simmers	Research Biologist	WES, Vicksburg, MS
Mr. Antonio J. Palazzo	Research Agronomist	ERDC, Cold Regions Research and Engineering Laboratory (CRREL), Hanover, NH
Dr. Rufus Chaney	Research Agronomist	U.S. Department of Agriculture-Agricultural Research Service, Beltsville, MD
Dr. Steve Rock	Environmental Engineer	U.S. Environmental Protection Agency (EPA), Cincinnati, OH
Dr. Robert J. Fellows	Senior Research Scientist	Battelle Northwest
Dr. Paul Schwab	Professor of Soil Chemistry	Purdue University
Dr. Charles Reynolds	Research Physical Scientist	CRREL, Hanover, NH

in dredged material and develop guidelines on the application of phytoreclamation to dredged material, providing environmentally effective alternatives to dredged material management.

OVERVIEW OF DREDGED MATERIAL AND CONFINED PLACEMENT: The majority of phytoreclamation research and demonstration efforts have occurred on industrial, Department of Defense (DoD), and Department of Energy (DOE) sites. Although the working group participants were very familiar with the application of phytoreclamation in these areas, some had not been exposed to CDFs and the complexities of dredged material. WES personnel presented a brief overview describing the dredging process, CDF design, and contaminated dredged material management. Chemical concentrations of dredged materials studied previously were described including those from Indiana Harbor, Blackrock Harbor, and New Bedford Harbor. These dredged materials were representative of the higher concentrations of contaminants in dredged material considered for upland placement. A data summary of these materials is provided in Table 2. In addition, proposed application of phytoreclamation to Pearl Harbor dredged material was described.

The application of phytoreclamation to dredged material presents some challenges that are unique to dredged material. Dredged material comes from an aquatic environment and is initially wet and anaerobic after placement in a CDF. Subsequent drying and oxidation depend on dewatering and management techniques, which vary from site to site. Drying and oxidation of surface layers may result in physicochemical changes that may affect plant establishment and contaminant mobility. Although the surface layer of dredged material in a CDF may be dry and aerobic, deeper layers may remain anaerobic due to the physical design of CDFs and limited air penetration of the surface layers. Saltwater dredged material provides another level of difficulty for vegetation and in most cases must be leached to reduce soluble salts. Depth of dredged material in a CDF may be only a few feet to as much as 27 m (90 ft). Dredged material management is further complicated by the potential of elevated concentrations of multiple contaminants. The selection of plant species and methods of establishment will be determined by these factors.

Table 2
Selected Contaminants from Previous Dredged Material Studied, mg kg^{-1}

Parameter	Indiana Harbor[1]	Blackrock Harbor[2]	New Bedford Harbor[3]
Arsenic	36.8	22.9	8.66
Cadmium	22.2	22.4	35.4
Chromium	514	1651	754
Copper	266	2728.4	1730
Lead	933	397.8	2013
Mercury	0.262	2.0	2.59
Nickel	120	178.8	122
Zinc	3785	1307.1	3017
PCB 1242	<0.2	5.5	887
PCB 1248	29.4	NA	NA
PCB 1254	<0.2	9.3	662
Phenanthrene	210	5	9.6
Fluoranthene	175	6.3	8.7
Benzo(a)Pyrene	115	3.9	7.6

[1] Environmental Laboratory 1987.
[2] Brandon et al. 1991.
[3] Myers and Brannon 1989.

In some cases, particularly for saltwater dredged material, phytoreclamation will be initiated after the conversion of dredged material into a manufactured soil product. A manufactured soil may be processed with aged dredged material from an existing CDF or from freshly dredged sediment at a processing facility or CDF. Phytoreclamation strategies must be capable of addressing these specific needs.

DISCUSSIONS ON PHYTORECLAMATION APPROACHES TO DREDGED MATERIAL CLEANUP: A number of factors must be considered prior to initiating a phytoreclamation process in the field. Age and condition of dredged material in existing CDFs may determine the process selection. Freshly deposited material and material in some older CDFs will require dewatering prior to plant establishment. The selection of plant species will be contaminant and site specific as plants that are noted as effective in reducing certain contaminants may unfortunately not grow sufficiently in certain climates or soil types. Other difficulties may include the patent and/or licensing requirements to use some phytoreclamation processes and obtaining certain germplasms. All of these must be taken into consideration when developing a strategy for using phytoreclamation to reduce contaminant concentrations in dredged material. The group concluded that a standard sequence of events should precede any application of a full-scale phytoreclamation effort in the field. The phytoreclamation framework, described in Price and Lee (1999), should provide guidance in determining the most effective phytoreclamation approach if one is available. Application of phytoreclamation to the field must follow the most effective approaches determined in this framework.

In addition, the group discussed phytoreclamation processes, both published and in study, worthy of consideration for use in dredged material. It was noted that no single phytoreclamation process would be the cure-all for all contaminants. Each must be addressed separately. The following two sections describe the sequence necessary to select a phytoreclamation approach and recommendations on phytoreclamation processes for specific contaminants. Specific remarks are provided based on the professional judgment of working group participants. References are cited where provided in the discussions.

Sequence to Phytoreclamation:

1. **Determine Reclamation Goals:** If cleanup thresholds are available, the local authority in which the site is located or where the material will be used if transported offsite will normally determine reclamation goals or acceptable concentrations in the final soil product.

2. **Water Removal:** For phytoreclamation of freshly dredged sediment or in a ponded CDF, removal of water to support establishment of upland plants and other bioreclamation processes may be required. A number of mechanical approaches for dewatering have proven effective for CDFs (Headquarters, U.S. Army Corps of Engineers, 1987). Lee et al. (1976) determined that certain plants can facilitate dewatering and consolidation of fine-grained dredged material. Transpiration by plants can remove significantly larger quantities of water than simple evaporation of unvegetated dredged material. Plants that can be easily established on loosely consolidated dredged material and have large root systems that will reach anaerobic zones to facilitate water removal are necessary. Some examples of suitable plants include Eastern gamma grass and hybrid poplar trees. Selection will be dependent on specific needs. Under certain conditions, anaerobic dredged material may be blended with cellulose and biosolids to produce a manufactured soil product. The resulting soil product will have less free water and is ready for immediate establishment of plants for the phytoreclamation process.

3. **Selection of Plants to Achieve Goals:** The cleanup goals of each contaminant will drive the selection of a phytoreclamation process. Goals may be based on a soil concentration threshold or a bioavailability threshold. In situations where two or more contaminants require some form of reduction, phytoreclamation may have to occur sequentially or concurrently with other phytoreclamation, bioreclamation, or chemoreclamation processes. Phytoreclamation processes that are known or suspected to have effective results are discussed in the following sections by contaminant class.

4. **Screening and Quantification Testing:** It will be necessary in most cases with dredged material to conduct tests in controlled greenhouse environments to determine the plant growth response to dredged material and/or manufactured soil. Sturgis and Lee (1999) describe the manufactured soil screening test to determine blends of dredged material, cellulose, and biosolids most suitable for plant growth. The effectiveness of a phytoreclamation process should be evaluated prior to initiation of a field-scale demonstration, particularly where little information is known about the effectiveness of a particular phytoreclamation process on dredged material or manufactured soil. Due to the small volume of soil material used in the manufactured soil screening test, it is not suitable to

determine effectiveness of phytoreclamation in reaching reclamation goals. A plant bioassay procedure (Folsom and Price 1989), which uses a larger volume of soil material and provides for optimum water management, can incorporate the results of the manufactured soil screening test and be utilized for this purpose. More specifics on a framework to determine phytoreclamation effectiveness is provided in Price and Lee (1999).

Specific Recommendations for Dredged Material Contaminants:

1. **Heavy Metals:** Plants can readily accumulate some heavy metals and some plants may even hyperaccumulate certain metals. The metal-laden plant tissues can be harvested and properly managed. In some cases, metals can actually be recovered from plants containing high concentrations (% range) of metals and recycled. The group discussed a number of known investigations, published and unpublished, where plants have been used for heavy metal reduction in soils (Table 3). Due to proprietary protection of unpublished information, details on some of the items listed are not available. Most of these phytoreclamation processes for metals involve hyperaccumulation and removal of metal-laden plant tissues. Plant-assisted reduction of selenium (Se) and Mercury (Hg) includes volatilization through plant respiration. *Brassica juncea* has been suggested to hyperaccumulate lead (Pb) after chelates are added to soil, making the Pb more available. However, when metal chelates are added to Pb-contaminated soil, migration of chelated lead into surface and groundwater must be controlled. The group suggested that inactivation of lead through the addition of phosphate fertilizers and the formation of lead phosphate was a more economic and environmentally acceptable alternative. Chaney et al. (in preparation) summarizes approaches and progress in developing commercial phytoextraction systems for these and other metals using metal hyperaccumulator plants.

   In general, the group concluded that, based on the relatively low concentrations of metals in dredged materials compared to those in mining and industrial sites, the economical application of phytoreclamation to dredged material may be limited to situations where heavy metal content of dredged material requires reduction to some lower acceptable concentration.

2. **Petroleum Hydrocarbons:** The working group concluded that the application of phytoreclamation for reduction of petroleum hydrocarbons may be more feasible than for heavy metals in dredged material. The use of plants to reduce petroleum hydrocarbons from soil has been demonstrated on a number of sites using the process of degradation rather than actual uptake. As shown in Table 4, a number of plant species have been employed for this process. Most of the species will require a pH near 7.0 for optimum growth and aerobic conditions to promote a viable and active plant-associated microflora. Fertility levels would also need to be maintained for the same reasons. Depending on polycyclic aromatic hydrocarbon (PAH) concentrations and physical conditions of the dredged material, significant reduction of 3- and 4-ring PAHs can be accomplished in as little as one year. Larger ring PAHs will degrade more slowly and require more time and possibly a combination of phytoreclamation and bioreclamation. For total recoverable petroleum hydrocarbons (TRPH) the same applications apply as for PAHs, and in addition, TRPHs may require the application of polyacrylamide or PAM.

Table 3
Suggested Phytoreclamation Considerations for Metals in Dredged Material

Metal	Plant Species	Leaf Concentration mg kg^{-1}	Soil Conditions	Group Remarks (References)
Arsenic	"Florida Plant"	NA	NA	Not ready for use (None specified)
Cadmium	*Thlaspi caerulencens*	1,800	NA	Great Lakes Region, 5-10 kg/ha/year (Li et al. 1997)
Copper	*Aeollanthus biformifolius*	13,700	NA	Not ready for use (Brooks and Radford 1978)
Chromium	"ET[1] Plants"	NA	NA	Reduction of chromate required (None specified)
Cobalt	*Haumaniastrum robertii*	10,200	NA	NA (Brooks 1977)
Mercury	Poplar Sp. Canol Sp.	NA	NA	Volatilization (Rugh et al 1996)
Lead	Plants not recommended	NA	Apply Phosphate	Inactivation of lead using phosphate fertilizer preferred (Chaney, Ryan, and Brown 1999; Berti and Cunningham (1997)
Nickel	*Phyllanthus serpentinus*	38,100	NA	NA (Kersten et al. 1979)
Selenium	*Astragalus racemosus*	14,900	NA	Needs EPA approval; hyperaccumulation /volatilization (Beath, Eppsom, and Gilbert 1937)
Zinc	*Thlaspi calaminare*	39,600	NA	Effective (Reeves and Brooks (1983)

[1] Evapotranspiration.

Table 4
Suggested Phytoreclamation Considerations for Petroleum Hydrocarbons

Compound	Plant Species	Soil Conditions	Remarks
PAHs (3-4 Ring)	Bermuda White Clover Tall Fescue Birdsfoot Trefoil St. Augustine Weeping Love Wheat Barley Ryegrass (A/P)[1]	pH near 7.0 High Fertility Aerobic	Degradation is most likely process. Can reduce concentration to <1 ppm. Can achieve 60-90 percent reduction in one year (Lee et al., in preparation)
PAHs (5-6+ Ring)	Same as above	Same as above	Degradation is slower. Achieve 40-50 percent reduction in 2-3 years. (Lee et al., in preparation)
TRPHs	Same as above	Same as above Application of PAM	Need to analyze individual PAHs and TRPHs (Schwab 1997)

[1] Annual or perennial.

3. **Polychlorinated Biphenyls (PCBs):** The group agreed that the phytoreclamation of PCBs is not an effective technology at present. Some studies are being conducted using tree species as shown in Table 5. The degradation of PCBs by phenol-like root excretions has been identified as a likely process. It was indicated that sequential wet/dry soil conditions and inoculation with specific microbes is necessary for success. Phytoreclamation may be more effective on PCBs in conjunction with a bioreclamation process such as biomounds.

Table 5
Suggested Phytoreclamation Considerations for Polychlorinated Biphenlys

Compound	Plant Species	Soil Conditions	Remarks
Aroclors	Mulberry	Sequential wet/dry	Inoculate with microbes. Phenol-like root excretion (Fletcher, Donnelly, and Heagle 1995)
Cogeners	Hackberry	Sequential wet/dry	Analyze congeners first and last; aroclors always. Longer time required. (None specified)

4. **Pesticides and Dioxins:** Although pesticides are present in very low concentrations in many sediments, particularly near agricultural lands, there have been few situations in dredged material placement where they were considered a problem. No plant species are indicated in Table 6. If pesticides were a concern, the primary approach to reduce adverse effects would be to stabilize and render the compound inactive. This can be achieved by the addition of compost materials using the manufactured soil technology.
Dioxins are sometimes present in sediment from a number of sources including historical spills and discharges from paper mills. At present no reported phytoreclamation processes have been shown to degrade or remove dioxins from dredged material or any other soil material.

Table 6
Suggested Phytoreclamation Considerations for Pesticides and Dioxins

Compound	Plant Species	Soil Conditions	Remarks
Most Pesticides	NA	Compost additions Manufacured soil technology	Stabilize and render inactive (Schnoor 1997; Cole, Liu, and Zhang 1994)
Dioxins	NA	NA	No reported degradation in NY/NJ study (Lee et al., in preparation)

SUMMARY AND CONCLUSIONS: The conclusions of the Phytoreclamation Working Group meeting were that phytoreclamation of dredged material would not be as readily effective as its application to more heavily contaminated industrial sites. There are many instances, however, where phytoreclamation would be a cost-effective alternative compared with other cleanup alternatives including no-action alternatives (no-action alternatives may require long-term ecosystem monitoring). These include instances where reuse of contaminated dredged material as manufactured soil is considered but contaminants such as metals and PAHs limit its use. Phytoreclamation of some metals and petroleum hydrocarbons in dredged material is ready for demonstration while phytoreclamation of PCBs, dioxins, and other contaminants is inconclusive at this time and will require further research before demonstration-scale testing is warranted. There is still disagreement among Federal agencies and between State and Federal agencies on acceptable soil reclamation goals. These disagreements concern mostly the question of soil concentration versus bioavailable concentrations of contaminants. Some contaminants, such as lead, can be present at elevated concentrations and yet not available for uptake by plants and animals. Until universally acceptable goals are established, local authorities will more than likely set reclamation goals.

Demonstrations of phytoreclamation on a plot scale in the field should be preceded by careful selection of plant materials and necessary soil amendment and management techniques. Manufactured soil screening tests to determine plant/manufactured soil blend interactions and quantification of effective contaminant degradation/uptake using plant bioassays in controlled conditions are recommended prior to initiating field demonstrations.

ADDITIONAL SOURCES FOR PHYTORECLAMATION INFORMATION: A previous technical note (Price and Lee 1999) provides additional information on determining the suitability of dredged material for phytoreclamation. Plant-assisted cleanup of contaminated soil materials and water is readily accepted by the public due to its image as a 'green clean' technology. As such, there is a great deal of interest in phytoreclamation research and commercial application of phytoreclamation processes. A number of phytoreclamation sites can be found on the Internet and new ones are added frequently. One informative site can be found at *http://www.plaii.com/Matrix/section4/4_5.html#poc*. Some other sites that include extensive bibliographies can be found at the following Web addresses: *http://www.rtdf.org/public/phyto/phytobib/biba-b.html*, *http://www.aehs.com/phytohome.htm*, *http://hano.tricity.wsu.edu/~vmedina/biblio.html*, and *http://www.wes.army.mil/el/phyto/pubs.html*.

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